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**AUTOMATED FIBER PLACEMENT—EVOLUTION
AND CURRENT DEMONSTRATIONS**

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ABSTRACT

The automated fiber placement process has been in development at Hercules since 1980. Fiber placement is being developed specifically for aircraft and other high performance structural applications. Several major milestones have been achieved during process development. These milestones are discussed in this paper.

The automated fiber placement process is currently being demonstrated on the NASA ACT program. All demonstration projects to date have focused on fiber placement of transport aircraft fuselage structures. Hercules has worked closely with Boeing and Douglas on these demonstration projects. This paper gives a description of demonstration projects and results achieved.

CONFERENCE

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AUTOMATED FIBER PLACEMENT EVOLUTION

Hercules filament winding experience dates back to 1957. We have used this experience to develop a new automated process to accurately place and compact prepreg tow material that meets the requirements for aircraft applications. The automated fiber placement process (also known as automated tow placement) has been significantly improved over the last 10 years and is now production ready.

 In the late 1970s, Hercules identified composite aircraft and space structures as possible applications for automated filament winding. Although filament winding was ideal for rocket motor cases, it was not necessarily a good process for aircraft and space structures. These parts were seldom symmetrical bodies of revolution; many had complex compound curvatures with concave surfaces. Filament winding relied on tension and geodesic paths to keep the material in place and was limited in ply angle orientation capability. On complex structures, filament winding was not practical. Automated tape layup was limited to relatively flat surfaces, and the process was very immature at the time.

A machine was needed that would lay material down at any orientation from 0 to 90°, and that could handle both symmetrical bodies of revolution and complex contoured surfaces. Structures fabricated on this machine needed to be equivalent in performance properties to structures fabricated with prepreg tape and fabric materials. It appeared that the machine would be a hybrid of filament winding, tape laying, and some new technology.

In 1980, the design of a six-axis machine that could follow complex contoured surfaces while placing and compacting material directly on the surface was started by Hercules engineers at the Clearfield, Utah filament winding facility. It was originally called "advanced filament winding" or "six-axis filament winding."

Two years later, the design was complete and procurement of machine elements was under way. In 1983, Hercules assembled the first six-axis machine. This machine incorporated a three-roll wrist (designed for the robotics industry) along with a horizontal profile machine modeled after the state-of-the-art filament winding machines designed and built by Hercules for in-house use.

The delivery system consisted of a standard dry fiber creel, a series of redirects, a hot melt resin impregnation station, and a sophisticated delivery head. The delivery head was capable of delivering 12 tows of material. It was designed to cut one tow at a time, and add one tow at a time when commanded by the software. The cutter and the adder were indexed by two small stepper motors. The tows came in on one level, but were spaced approximately one tow width apart to allow clearance for the cutter and adder for each tow. The tows were converged back together as the tray cavities came closer together. The final delivery roller consisted of a segmented roller, with each segment capable of compacting two tows at a time. These roller segments floated individually to provide compaction of contoured surfaces, while allowing individual fiber speeds across the band.

The new machine and process were distinguished from standard filament winding by being designated "fiber placement," because the individual tows of fiber were now being placed precisely on the surface of the part and compacted in place as they were applied. Another name often used today is "automated tow placement."

The machine and process described above were used to fabricate the Sikorsky ACAP tailcone (Figure 1). Although the ACAP part was successfully fabricated, a

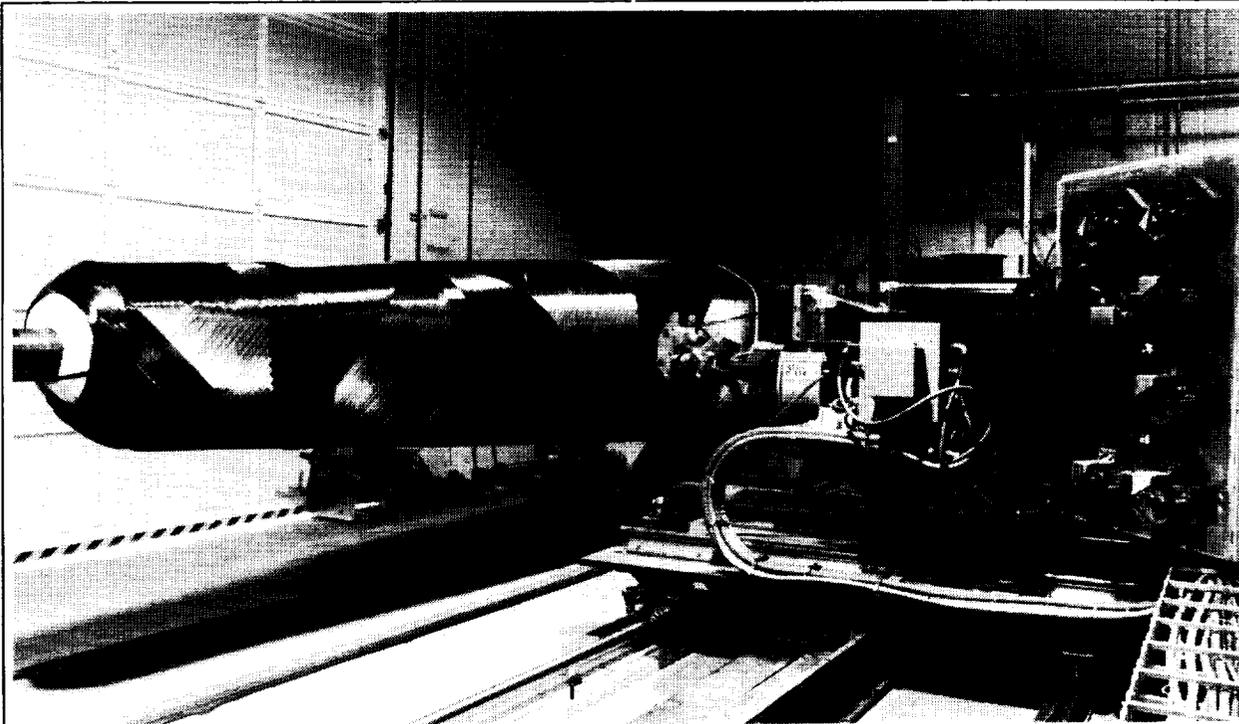


Figure 1. The six-axis automated tow placement machine was used to fabricate the Sikorsky ACAP tail cone.

combination of filament winding and fiber placement methods was used. A need to improve the technology in several areas became apparent because the operation did not proceed as smoothly as the theory indicated. However, it was a significant step in the evolution of fiber placement.

The software required to program the six-axis machine was developed by Dr. Russ Wilhelmsen, a mathematician and computer scientist with a special ability to manipulate spatial geometries. Development and refinement of an off-line programming system for fiber placement has progressed significantly over the past several years.

From the early machine and delivery system to the production ready system available today, there have been many improvements (Figure 2). The more significant evolutionary steps are outlined in the following paragraphs.

MACHINE DEVELOPMENT MILESTONES

Prepreg Tow

Impregnation of dry fiber with a hot melt resin delivery system on the machine had some definite cost advantages. However, resin content control was a problem because the process featured a variable rate with stop and go inconsistencies. Prepreg tow was ordered from material suppliers starting in 1985. The first materials

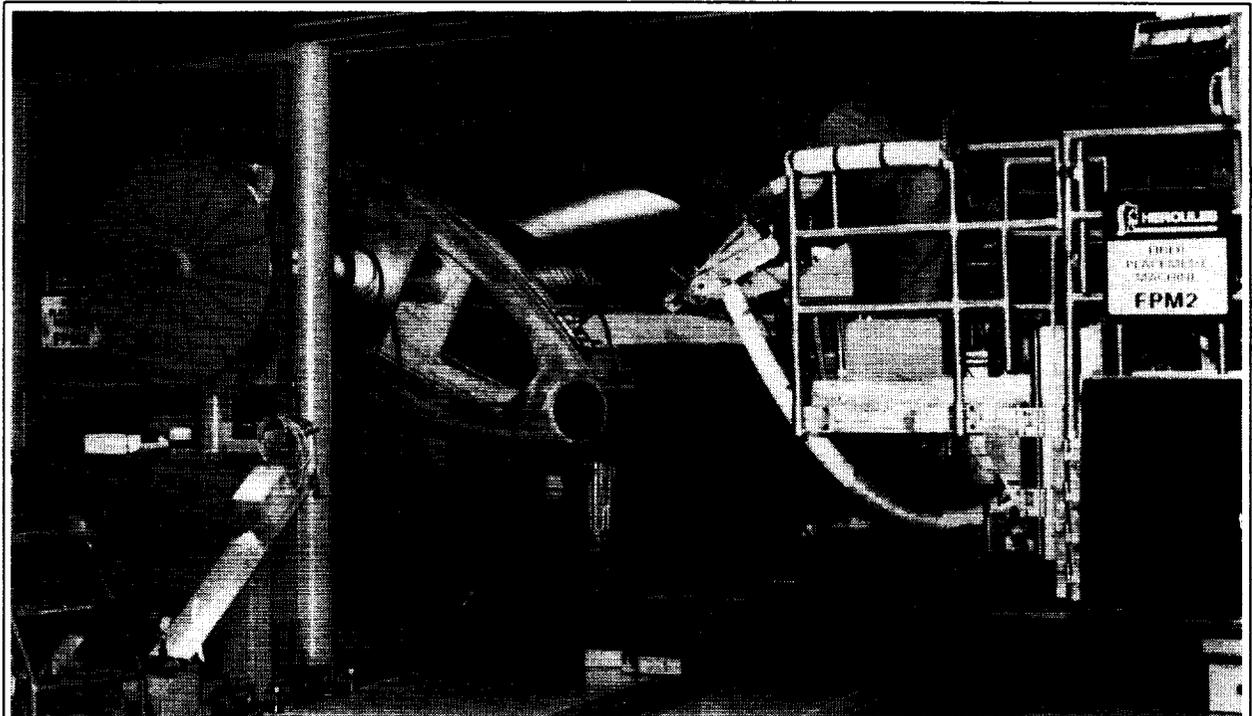


Figure 2. The seven-axis automated tow placement machine incorporates many improvements over earlier machines and delivery systems.

used were made from solvent-based impregnation systems. The materials worked well as long as the residual solvent level was well controlled. Too much solvent made the material very sticky and soft. Mechanical properties testing on the Large Fuselage MANTECH Program showed how difficult it was to get all the residual solvent out of the tow during final part cure. This resulted in lower Tg properties for parts made using solvated prepreg tow.

To improve Tg properties, the Hercules Materials group developed a hot melt prepreg tow process for the Large Fuselage Program (later known as the V-22 Aft Fuselage Demonstration). Since then, the Hercules hot melt prepreg tow process has been greatly refined. Today's process delivers a well-controlled material form for fiber placement. The cost of prepreg tow today is slightly higher than prepreg tape because of the low volume in use. It will become a lower cost material form than prepreg tape as the volume increases.

Bi-Directional Tensioners

One of the key elements in fiber placement is the maintenance of a low, consistent tension. The early delivery creels were capable of applying tension, but did not have the ability to respond to a slack fiber condition, which occurs regularly in fiber placement as a result of the wrist motion on complex surfaces. Simple mechanical devices were used on fiber placement machine No. 1 (FPM1) to keep fibers tight. Fiber placement machine No. 2 (FPM2) was equipped with tensioners

that would allow material to pay out as needed and would take up material on the spool if it attempted to go slack, all the time maintaining constant tension on each tow.

Refrigerated Creel

Prepreg tow does not use backing paper and is spooled on a way wound package to facilitate removal. Some materials can be spooled at room temperature and unspooled successfully, but the majority of them will not. Hercules added refrigeration to the fiber delivery creels to prolong the life of the material, to allow for clean unspooling, and to protect the material from slump when it was not rotating. This has reduced the problems in the creel to near zero.

Ribbonization

Thermoset prepreg tow is in a soft pliable material form. When it is manufactured, the supplier tries to control the width and thickness profile of each tow. Typically, a width control of ± 0.025 inches can be guaranteed by the prepreg supplier for a way wound package. After the spools are loaded onto the fiber placement delivery creel, the fiber must pass through several redirects before it enters the delivery head. Depending on the severity of the fiber path (based on wrist position for a given geometry), the soft pliable tow will often change shape slightly while traveling this path. With a stringent requirement to deliver the individual tows onto a structure with no more than a 0.030-inch gap or overlap between tows or between bands of tows, the tow width variations just described could easily exceed the gap/overlap requirements. To avoid the inconsistencies described, Hercules developed a technique to ribbonize (control the width and thickness of each tow) within the delivery head. This has allowed us to deliver a wide variety of materials and to accommodate last minute design changes from customers. This ribbonizing module can be easily removed from the head if it is not required.

Two Tier Delivery

To accommodate individual tow cut and add mechanisms, the tows in the delivery head are separated into two tiers with a one-tow width separation between each tow. The two tiers of tows are merged together near the delivery point. This allows a straight tow path through the head. The individual actuators for each tow allow any tow or combination of tows to be cut or added back in simultaneously.

Heavy Duty Wrist

A new roll-bend-roll wrist was designed and put into use on FPM2 to accommodate the high compaction forces and newer generation delivery heads. This new wrist was a Hercules design and incorporated a series of compact motor and non-backlash gear assemblies into a wrist package that maintain a high degree of flexibility on each of the three axes.

Large Crossfeed Travel

For large parts with severe cross section changes and for parts where material must be placed on the end of the part near the shaft or rotational centerline, a flexible wrist and a large crossfeed travel are required. Hercules designed FPM2 with 8.5 feet of crossfeed travel, and 1.5 feet of that travel beyond the spindle centerline. This feature was very helpful in fabricating the V-22 aft fuselage, a demonstration boat hull, and a 4-foot diameter sphere. It is also useful to meet production schedules that require the manufacture of widely different part geometries.

Synchronization

To have a tow start and stop accurately on the surface of a part required the development of synchronized motion between the rate at which new tows were being added and the rate at which material is being applied to the surface of the part. It also required look aheads in the software. These features were accommodated in later generations of the delivery head.

Heating and Cooling Zones

Over years of making parts, Hercules learned that strategic heating and cooling of the tows as they are delivered aided in the effective processing of the materials. The tows are cooled to reduce tack and to stiffen them so that they can be fed or pushed. The tows are heated in the ribbonizer to condition their width/thickness control, and are heated slightly at the laydown point to increase the tack characteristics (resin dependent).

Direct CATIA and IGES CAD Link to Off-Line Programming

To ensure that the complex surfaces being programmed are identical to the ones used in the product and tool design of the structures, Hercules developed direct transfer links from CATIA and IGES to feed three-dimensional CAD data to the fiber placement machine's off-line programming system. This direct link allows a rapid, accurate transfer of surface data.

Simulation Software

The need for the ability to estimate manufacturing times before the parts are actually built became apparent early in machine development. Hercules developed software to simulate the actual manufacturing times based on a given part geometry and the kinematics of the machine in which it is to be processed. This is a great help in planning work schedules, estimating costs, and in evaluating design changes to the machine. Hercules also has graphic simulation of the machine applying the material to the structure that can be used to verify that everything is in order before part fabrication.

Data Logging

The machine control system software has been customized over the years to provide a variety of useful data for the fiber placement operator and engineer. Some of these data include: laydown rates, off part times, machine down times, time stamps, system diagnostics, ply and circuit data, time to complete, etc.

These are only some of the significant areas where the evolution of the fiber placement machine technology at Hercules has been apparent. The other measure of the advances in technology can be seen by the quality and types of parts that are being fabricated today. The NASA ACT Program is a good illustration of some of the current work.

CURRENT DEMONSTRATIONS

Hercules ACT Program

The Hercules NASA ACT Program was established to demonstrate and validate the low cost potential of the automated tow placement process for fabrication of commercial aircraft primary structures. It is currently being conducted as a cooperative program in collaboration with the Boeing ATCAS program. Hercules is

responsible for fabrication of test panels that are representative in design of commercial aircraft fuselage Section 46 crown, keel, and side quadrants. Boeing is responsible for panel design and testing (Table I). All panels are fabricated using the automated tow placement process.

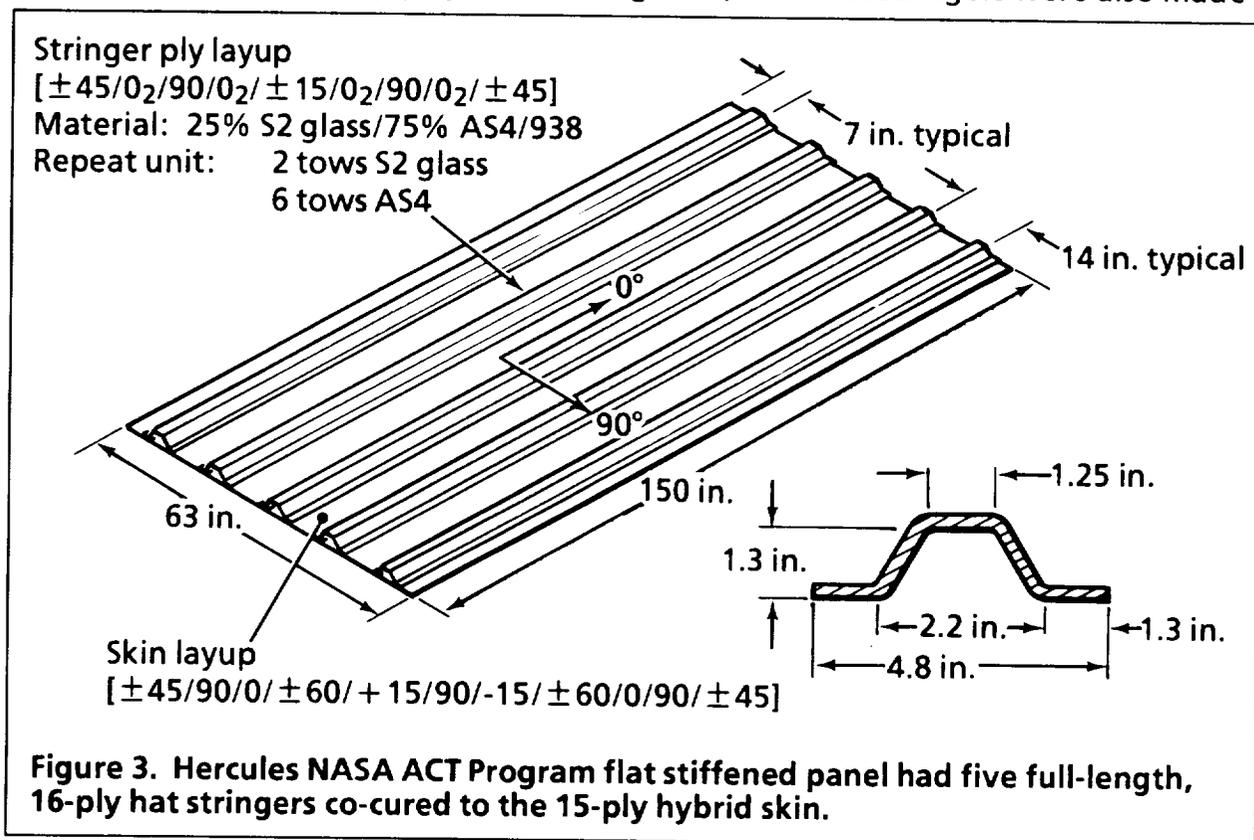
Table I. Test Matrix for Boeing/Hercules ACT Program Integration

Fuselage Quadrant	Test Article	Undamaged Elements	Tension with Damage	Shear with Damage	Comp. with Damage	Bi-Tension with Damage	Comp/Shear with Damage
Crown	Flat, unstiffened skin panels, 60 inch X 150 inch		2				
Crown	Flat, stiffened panels, 63 inch X 150 inch		1				
Crown	Curved, stiffened panels, 65 inch X 72 inch					1	
Keel	Flat, coupons, 35 inch X 60 inch				1		
Keel	Flat, stiffened panels, 30 inch X 44 inch				6		
Keel	Curved, stiffened panels, 30 inch X 44 inch						1
Window belt	Tension coupons with thick taper 35 inch X 60 inch	1					
Window belt	Curved panel with taper and cutout, 40 inch X 40 inch		1				
Window belt	Panel with double window frame 40 inch X 40 inch			1			

Program activities to date have focused on the fuselage crown quadrant. The Hercules program includes four large test panels for the crown task. Stiffened, unstiffened, flat, and curved panels have been fabricated for tension testing. A hybrid material form was used on two of the panels and the other two panels were made with all graphite materials. The hybrid material consisted of 25% S2 glass and 75% AS4 6K fiber. The glass and graphite tows were impregnated with Fiberite 938 resin. The glass/graphite hybrid material form is produced on the tow placement machine in a 24-tow band with repeat units of two tows of glass and six tows of graphite. The all graphite material form was AS4 6K fiber impregnated with Fiberite 938 resin.

The flat unstiffened panels were both 63 inch \times 150 inch 15-ply tension fracture panels. One panel was 100% graphite and the other was made with the glass/graphite hybrid material form. Both panels were autoclave cured using a 350°F and 100 psi cure cycle. Both panels looked good, and no defects were found with NDI. These panels were fabricated in July 1991 and were delivered to Boeing for testing. Both panels were tested and results were excellent when compared to prepreg tape layup panels.

The 63-inch \times 150-inch flat stiffened hybrid panel was cured and delivered in early 1992. This panel was stiffened with five full-length 16-ply hat stringers that were co-cured to the 15-ply hybrid skin (Figure 3). The hat stringers were also made



with the glass/graphite hybrid material form. The hat stringers were kitted from a flat tow-placed hybrid panel and were hot drape formed. The formed stringers were trimmed to size and fitted with a molded silicon rubber cure mandrel. The stringer/cure mandrel assemblies were located to the panel inside mold line (IML) (Figure 4). A layer of film adhesive was laid up under the skin flanges of each hat stringer. A peel ply was used on the panel outside mold line (OML) and IML surface. After the stringers were located, a molded graphite flex caul was installed on the IML of the panel assembly. The assembled panel was then vacuum bagged and autoclave cured at 350°F. After cure, the panel was trimmed to size, and the molded silicon rubber stringer cure mandrels were removed without difficulty. Quality of the panel was good, and no defects were found with NDI (Figure 5). Boeing will test this panel for axial damage tolerance.

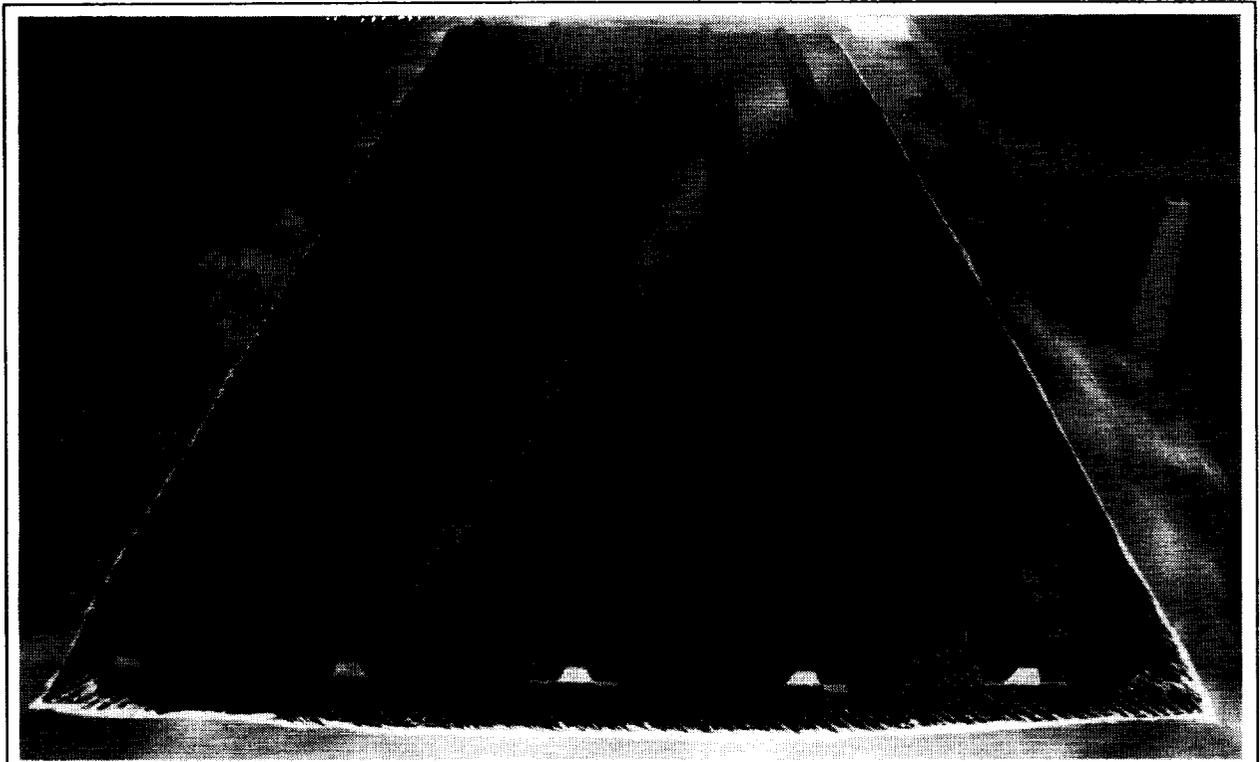


Figure 4. The hybrid panel/skin/stringer assembly was located to the panel IML.

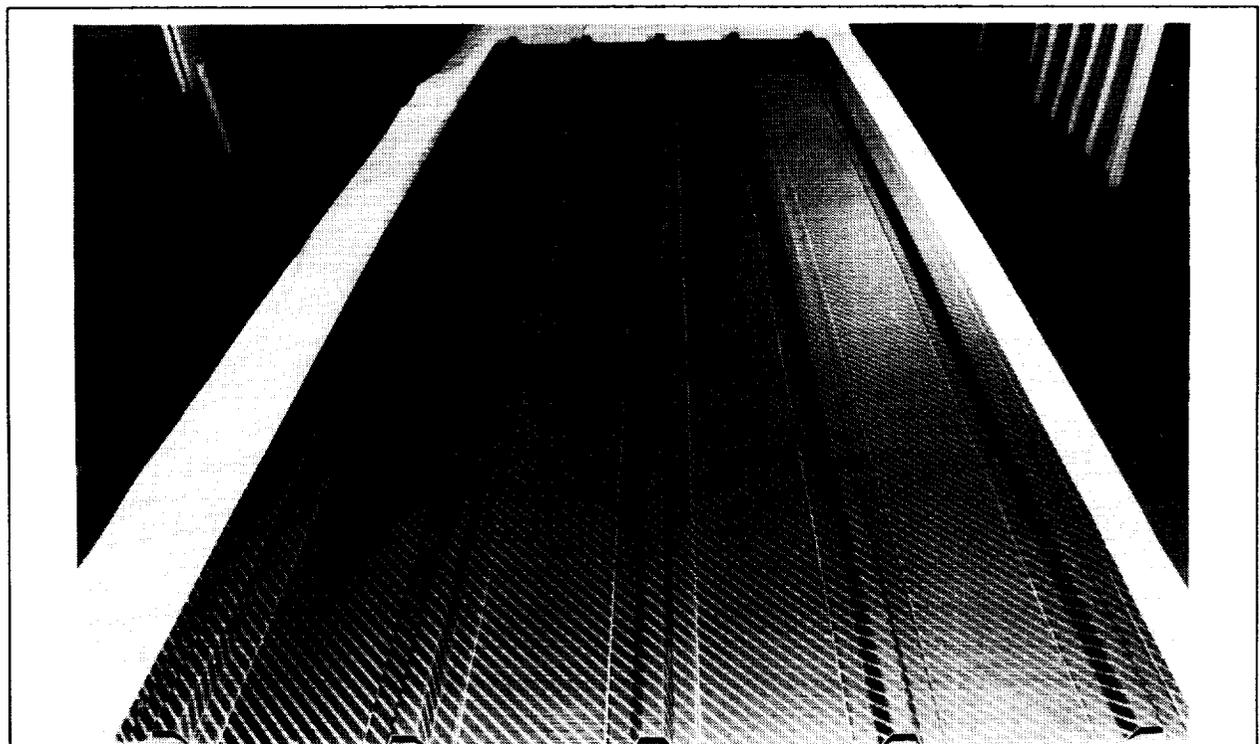


Figure 5. The cured hybrid panel quality was good; no defects were found with NDI.

The only curved panel for the crown task of this program is a large 65 inch × 72 inch panel with a 122-inch radius. This panel will have four hat stringers and three braided resin transfer molded (RTM) "J" frames. The stringers are co-cured with the panel skin and the precured frames are co-bonded to the skin. Fabrication of this panel is similar to the flat stiffened hybrid panel, except for the IML tooling to achieve the co-bonded frames. Both the skin and stringers were made on the tow placement machine. Skin and stringers are all graphite AS4 6K/938. Stringers are kitted from a flat tow-placed panel and are hot drape formed. The IML tooling is somewhat different in that the molded flex cauls are not full length, but are short pieces that are positioned over the skin/stringers between the frames. The frames are on 22-inch centers. The panel will be assembled and cured on an Invar OML cure mold. At the time this paper was prepared, the tow placement operations were finished and cure of the panel was expected late in May 1992. The tow-placed skin and stringers were stored in a freezer.

Activities on the keel task of the Hercules program will start in mid 1992. Designs for the keel test panels are being defined by Boeing. Hercules new 8553 toughened epoxy resin has been selected for the keel test panels.

Hercules ACT Subcontracts

Hercules currently has subcontracts from the Douglas ICAPS Program and the Boeing ATCAS Program (Table II). All Hercules NASA ACT-related subcontracts are based on the automated tow placement process, and all subcontracts to date have been fuselage related. Our subcontract from Douglas for tow placement of subscale fuselage panels was mostly completed in 1991. The contract has not been closed, and we are talking with Douglas about extending and modifying the contract for additional work scope. We have several ongoing Boeing ATCAS subcontracts at this time, and several subcontracts were completed during the past year.

Table II. Hercules ACT Subcontracts

Boeing ATCAS	<ul style="list-style-type: none"> • Flat tear strap panels (4 each) • Flat stiffened panel 63 inch × 150 inch • 3-foot × 5-foot curved stiffened panels (2 each) • 7-foot × 10-foot curved stiffened panels (2 each) • 7-foot × 10-foot curved stiffened panel (1 each) • 8-foot × 12-foot Invar cure mold
Douglas ICAPS	<ul style="list-style-type: none"> • 4-foot × 5-foot curved stiffened panel (6 each)

The manufacturing processes used to fabricate subscale fuselage panels for Douglas and Boeing were similar, but had distinct differences. Both the Boeing and Douglas Panels had tow placed skins and co-cured stringers. The Douglas design used "J" stringers, while the Boeing design used hat stringers. The Douglas panel stringers were hand laid up with prepreg tape, and the Boeing panel stringers were tow-placed material that was hot drape formed. Both panels were assembled and cured on an OML mold to achieve surface smoothness. The Douglas design has

mechanically attached frames, and the Boeing design has a co-bonded frame. Boeing also mechanically attached the frames on one of their large 7-foot×10-foot panels. The manufacturing processes used on both the Douglas and Boeing panels have been very successful. The quality of panels produced has been excellent.

Douglas ICAPS

The subcomponent panels fabricated for the ICAPS Program were 4-foot×5-foot curved panels on a radius of 118 inch. The tow-placed skins were 12 plies thick and the tape layup stringers were 20 plies thick. The panels were stiffened with six "J" stringers and three mechanically attached frames. The frames were attached to a shear tee that "mouse holed" over the stringers and was bonded to the panel skin. These shear tees also had a 4-ply doubler beneath them that was co-cured to the skin IML. The bonding of the shear tees and the attachment of the frames were done at Douglas.

The tooling concept for the ICAPS panels was somewhat different than anything used previously at Hercules. Our objective was a low cost, low risk tool concept to achieve a skin-to-stringer co-cure. Surface smoothness was also a consideration in selection of our tool concept. The stiffened test panels simulated aircraft fuselage skin; thus, the OML surface needed to be as smooth as possible. Some other objectives to be achieved with our tool concept were a uniform skin thickness, close tolerance in spacing of the stringers, and net shape of the stringer achieved during the panel cure process. To accomplish these objectives, we used a low cost aluminum mandrel to tow place the panel skins, which were then transferred to an OML mold for cure. The OML cure mold achieved the skin smoothness we wanted. The stringer spacing tolerance, uniform skin thickness, and net shape stringers were accomplished by using a molded caul sheet on the IML side of the panel during cure (Figure 6).

The IML flex caul was laid up on a master model machined from monolithic graphite (Figure 7). The model was machined to a 118-inch concave radius. Detail was also machined for the stringers and shear tee doublers. A thin, 4-ply, molded caul was laid up on the master model using prepreg graphite tooling fabric. The flex caul was cured at 250°F and postcured at 350°F.

The tooling concept was very successful. The tooling was simple and easy to use. We produced six 4-foot×5-foot panels for delivery to Douglas. All the panels were of excellent quality.

The fabrication process proved to be very simple and easy to duplicate. The 12-ply skins were tow placed on the aluminum mandrel and transferred to the aluminum OML cure mold (Figure 8). This was accomplished by setting the mandrel down on the cure mold and releasing the skin. The panel skin was then aligned to reference marks on the OML mold. The shear tee doublers were located to the skin IML by aligning to marks on the tool. The previously formed J-stringers were fitted

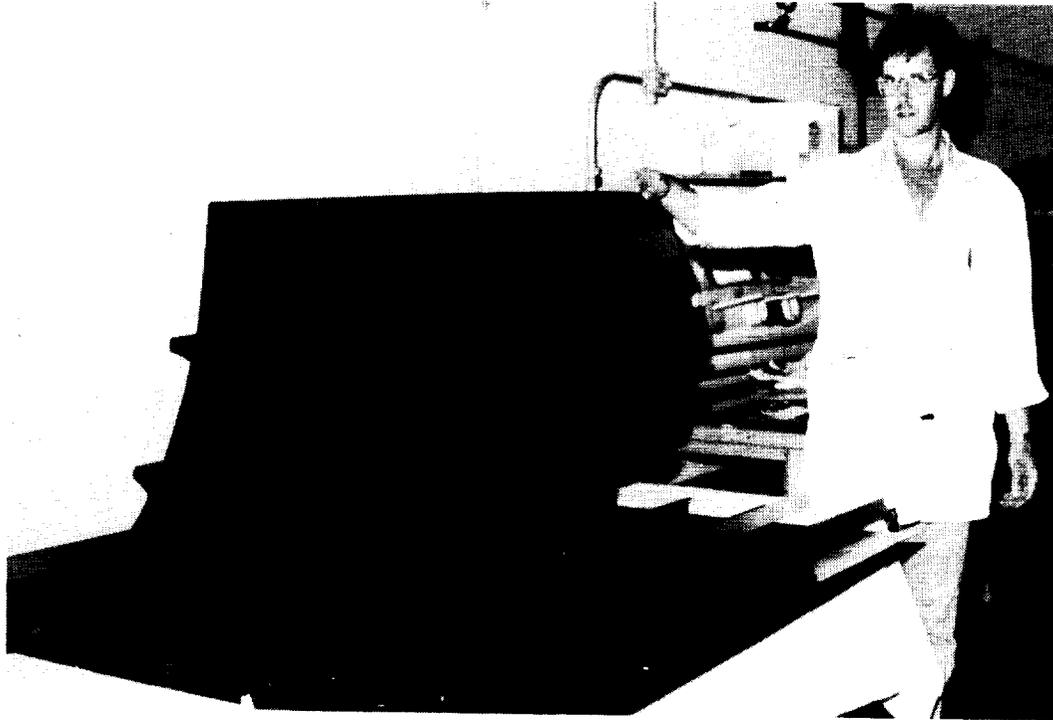


Figure 6. By using a molded IML flex caul, stringer spacing tolerance, uniform skin thickness, and net shape stringers were accomplished.

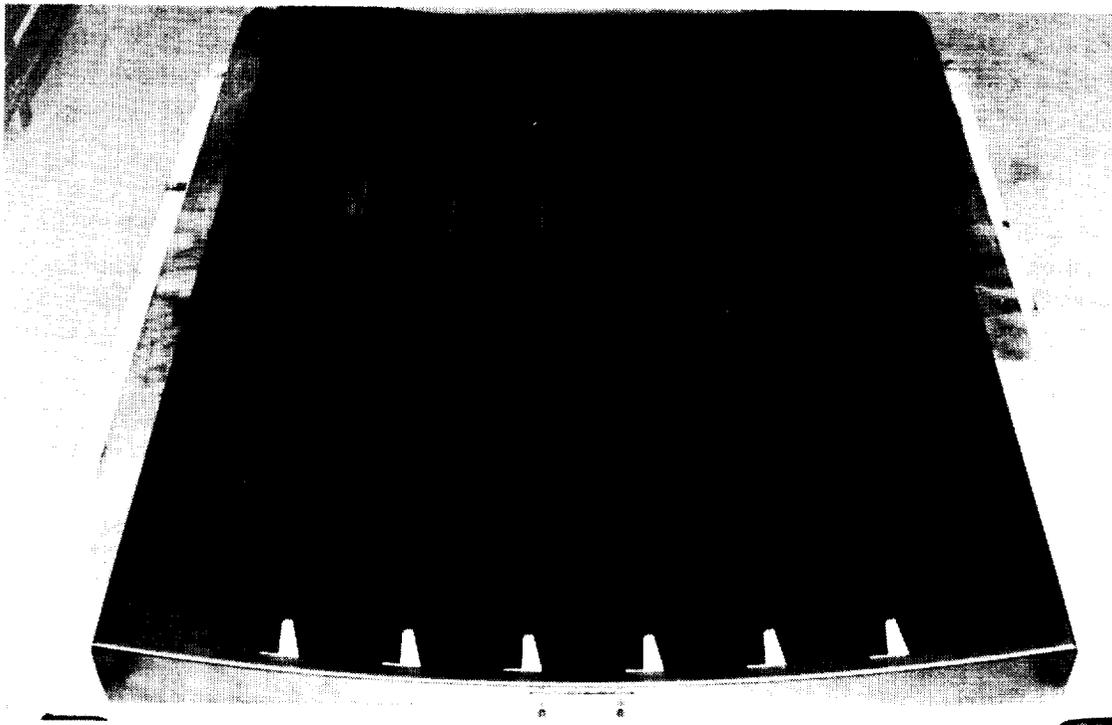


Figure 7. The IML flex caul was laid up on a monolithic graphite master model.

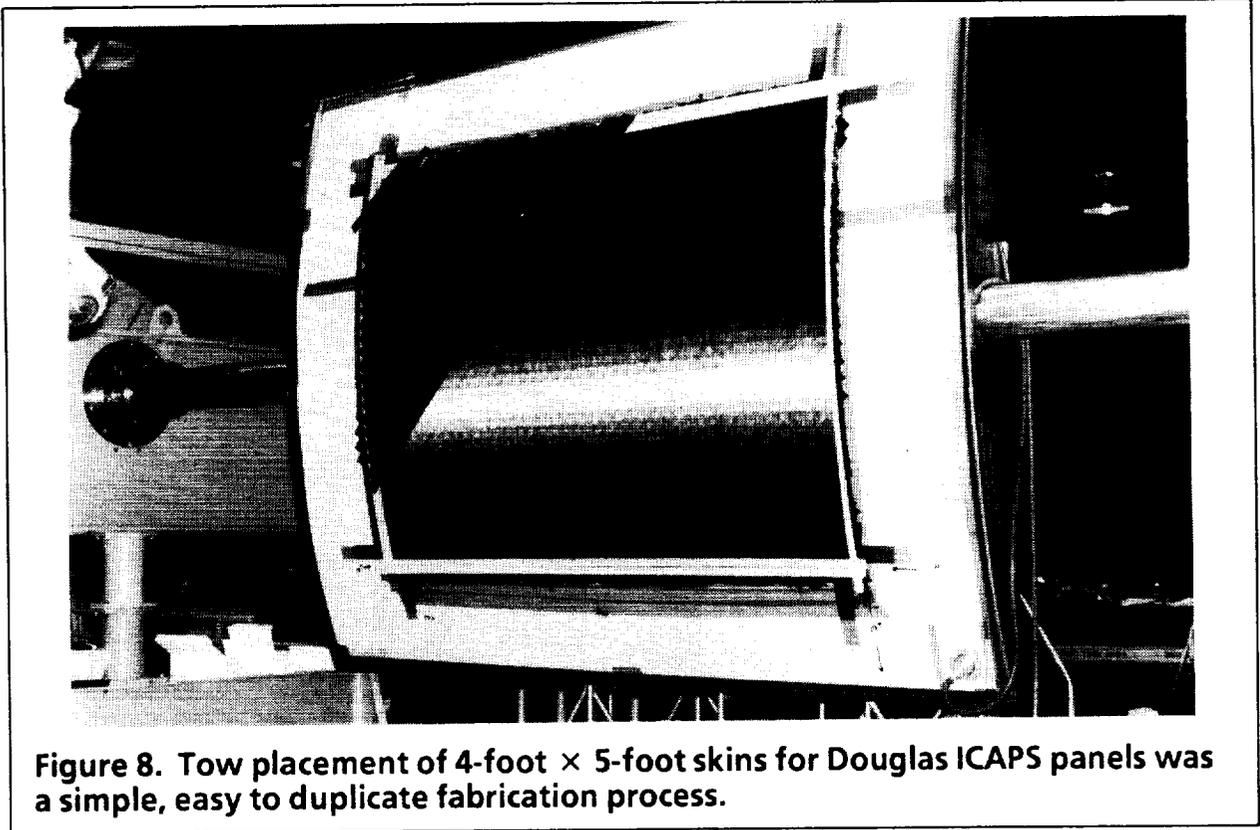


Figure 8. Tow placement of 4-foot × 5-foot skins for Douglas ICAPS panels was a simple, easy to duplicate fabrication process.

with a stringer cure mandrel, and the stringer/cure mandrel assemblies were positioned to the IML of the panel skin. Stringers were positioned using alignment marks on the tool. The molded graphite flex caul was located over the skin/stringer assembly and pressed down to the skin IML. Pressing the flex caul down corrected any error in stringer position. The completed assembly was vacuum bagged and cured in the autoclave.

After cure, the assembly was debagged and the tooling pieces were removed (Figure 9). The flex caul came off the panel with no problems. The stringer cure mandrels were removed by using T handles that screw into the sides of the cure mandrels. Removing the stringer tools was not a problem. The panel was deburred and trimmed to net dimension.

Dimensional and ultrasonic inspections were performed on each panel. No problem areas were discovered during NDI. Stringer spacing was well within tolerance. Overall quality of the panels was excellent (Figure 10).

Boeing ATCAS

Several subcontracts from the Boeing ATCAS Program are ongoing at the present time and several have been completed during the past year. We have fabricated both tooling items and tow-placed test panels for the ATCAS Program.



Figure 9. Removal of tooling from the Douglas ICAPS panel was completed with no problems.

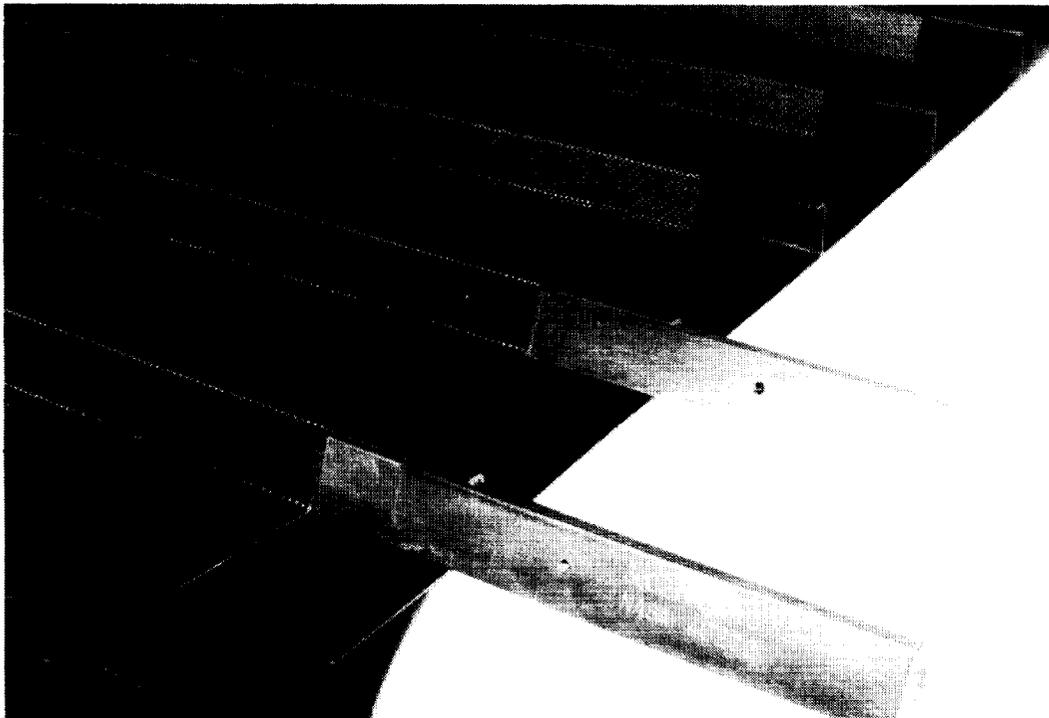


Figure 10. Stringer spacing was within tolerance, and overall panel quality was excellent.

All ATCAS panels to date have been crown quadrant designs. We have made flat unstiffened coupon panels and stiffened subscale crown panels for testing.

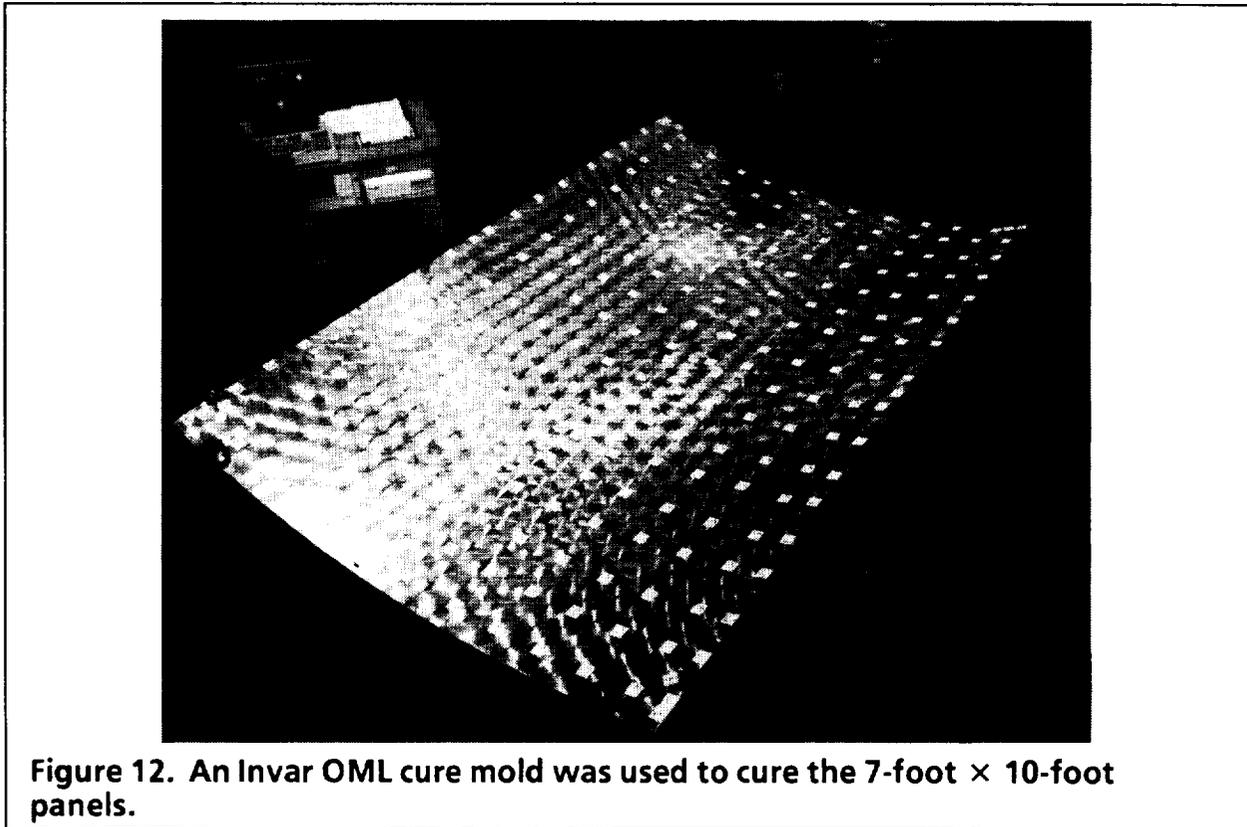
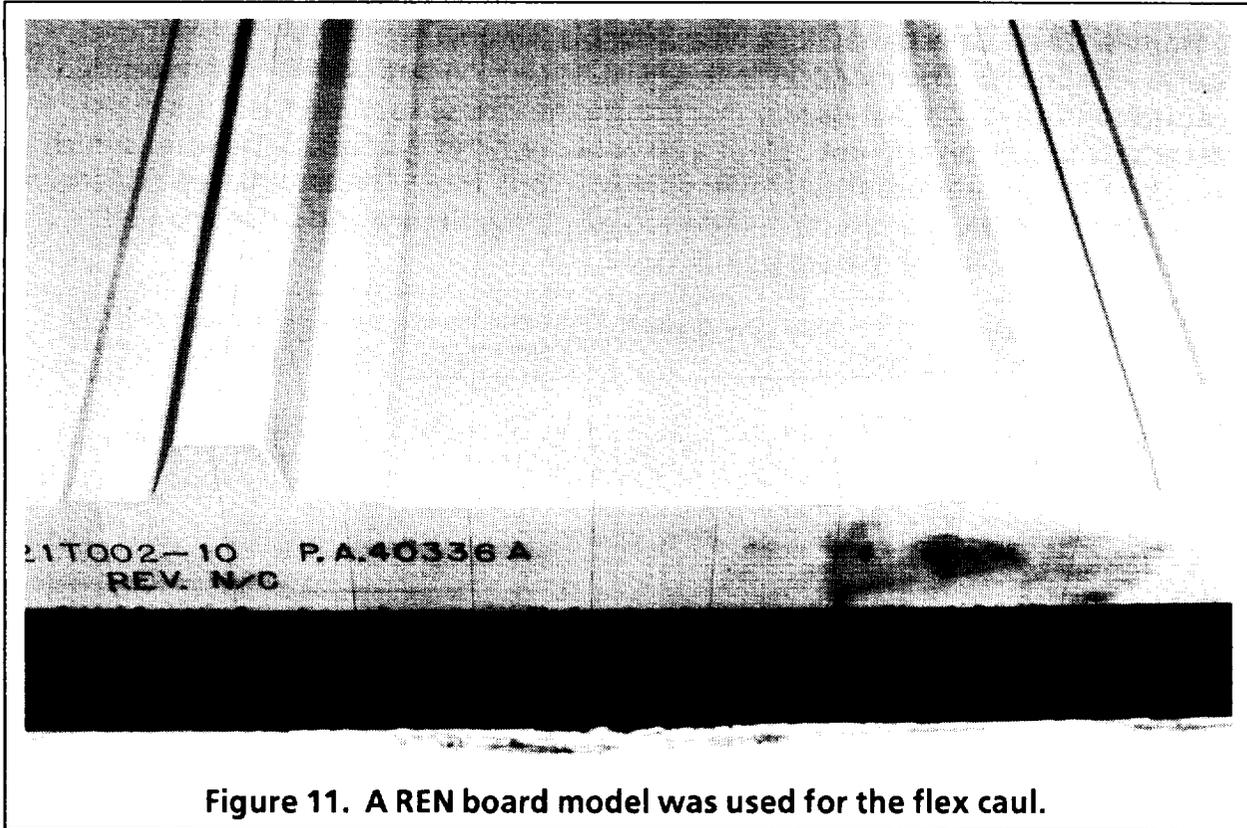
The Boeing designed manufacturing process for large Section 46 crown quadrants is similar to that used on the Douglas ICAPS subcomponent panels. The major exception is the co-bonded frames instead of mechanically fastened frames. Co-bonding of the precured braided RTM frames requires somewhat more complex IML tooling. The molded graphite flex caul cannot be a one-piece, full-length tool, but must be cut into short pieces that nest between the frames, which are located on 22-inch centers. Each caul piece must be sealed against the frames to prevent excessive resin bleed. Co-bonding the frames also requires a low coefficient of thermal expansion (CTE) OML cure mold to minimize tool growth at 350°F cure temperatures. Excessive tool growth would result in a mismatch in the skin radius and the radius of the precured frame that could cause a weak bondline. An Invar cure mold was used to cure panels with co-bonded frames.

The Boeing crown panel design is stiffened with hat section stringers instead of the "J" stringers used on the Douglas panel. Removing cure mandrels from a closed hat stringer proved to be a considerable problem. A machined metal mandrel with a silicon overwrap was tried first, and was very difficult to remove after cure. A molded silicon rubber mandrel was tried, and removing these tools after cure was not a problem. The combination of the molded silicon rubber stringer cure mandrel and the IML flex caul produced a very good quality hat stringer.

The master model used to layup the IML flex caul for the ATCAS 7-foot×10-foot panel was machined from REN 550 tooling board (Figure 11). We had used a machined monolithic graphite model for the Douglas ICAPS panels. The REN board model was of lower cost than a monolithic graphite model, and we used a low temperature cure tooling prepreg for the molded caul. The cured flex caul was postcured at 400°F. The REN model was machined in a flat configuration because its originally intended use was for a large flat stiffened panel. We used this flat master model to layup the caul for the 122-inch radius 7-foot×10-foot panels. The caul worked very well.

The OML cure mold used to cure the 7-foot×10-foot panels was made with an Invar tooling plate (Figure 12). The Invar plate was rolled to the 122-inch radius and the backup structure was welded on. The tool surface was then machined to the close tolerance radius. A frame fixture that bolts onto the cure mold was also made from Invar. This fixture clamps the frames and holds them in place during panel cure. The Invar cure mold was a very expensive tool.

We have subcontracts from the Boeing ATCAS Program to fabricate three 7-foot×10-foot stiffened crown panels. Two of these panels will have the co-bonded frames and one will have mechanically attached frames. The panel with the mechanically attached frames was finished first. The skin and stringers were cured in early April 1992. At the time this paper was prepared, work was in process on the 7-foot×10-foot panel with co-bonded frames.



The manufacturing process used on the ATCAS crown panels is similar to that used on the Douglas ICAPS panels, except for stringer fabrication and co-bonding the frames. The 13-ply panel skins were tow placed on a two-sided oval mandrel (Figures 13 and 14). The mandrel radius is 122 inches on both sides. The two-sided mandrel configuration was used only because the tow placement machine in its current configuration will not accept a 20-foot diameter cylindrical mandrel, which would be used to produce four crown panels on one tool. The tow-placed skins were transferred from the aluminum mandrel to a holding fixture and stored in a 0°F freezer while the stringers were being made.

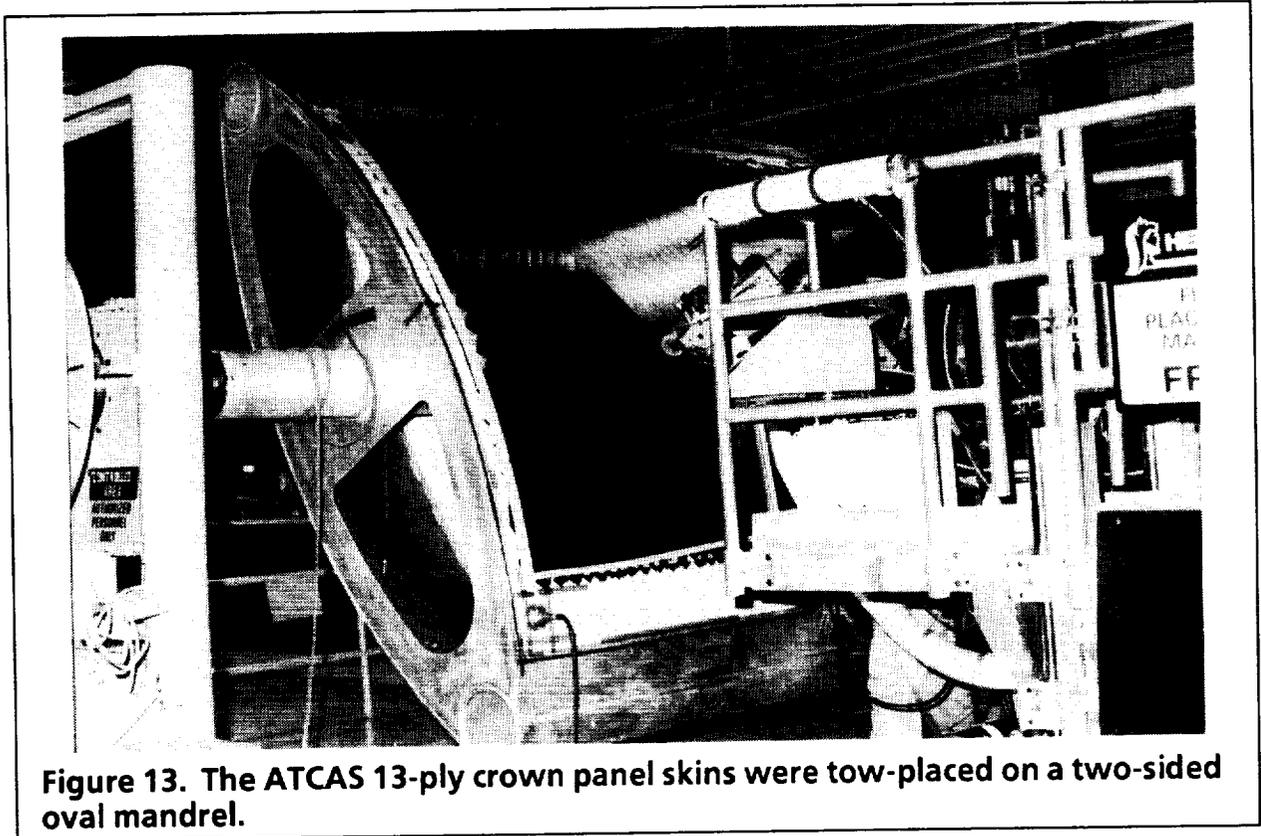


Figure 13. The ATCAS 13-ply crown panel skins were tow-placed on a two-sided oval mandrel.

The hat stringers were also fabricated with tow-placed material. A 13-ply flat panel was tow placed and the stringer charges were kitted from this panel. A machined aluminum female mold was used to hot drape form the stringers. The forming mold was heated in an oven. After the tool was removed from the oven, the flat stringer charges were laid up on the tool. As the material warmed up, it was hand worked down into the female mold. The molded silicon stringer cure tool was then pressed into the hat stringer. The mold and stringer were bagged and hot compacted. After compaction, the stringer was trimmed to size and stored in the freezer until all six stringers were finished and the panel was ready to be assembled.

ATCAS 7-foot×10-foot panels were assembled on the 122-inch radius Invar cure mold. A peel ply was laid down on the tool surface. The panel skin was taken out of the 0°F freezer and nested in the Invar cure mold. Strips of film adhesive were cut and laid up on the skin IML where the hat stringers were located. The film adhesive was only beneath the stringer skin flanges. The stringers were taken out of

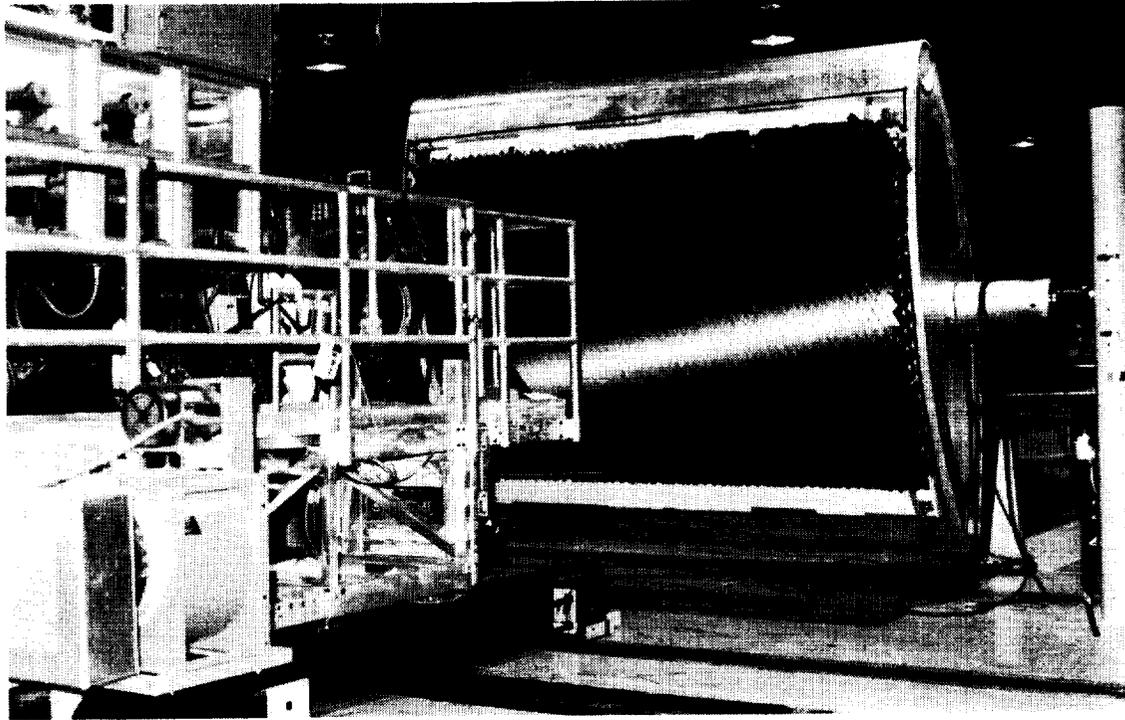


Figure 14. Tow placement of crown panel skins was accomplished on a 122-inch radius mandrel.

the freezer and located to the skin IML (Figure 15). A straight edge was used to ensure that the stringers were straight and precisely located. A peel ply was then cut and laid up on the assembled panel IML. The molded graphite flex caul was positioned on the assembled panel IML (Figures 16 and 17). The flex caul was taped to the Invar cure mold on all sides and the assembly was vacuum bagged.

The assembly process for the ATCAS 7-foot \times 10-foot panels with co-bonded frames differed somewhat from the process described above. Everything was the same up to where the stringers were assembled to the skin. At this point, the process changed. The precured RTM frames were located to the skin IML with a layer of film adhesive between the frame and skin. The frames were held in place with the frame clamp fixture described earlier in this paper. With the frames located and clamped down, the flex caul was installed. The flex cauls for the co-bonded panel were short pieces that nested between the frames, which were located on 22-inch centers. We used a peel ply on the IML of the co-bonded panel as well. After the flex cauls were pressed down to the skin IML, the assembly was taped and a molded silicon bag was installed on the assembly. The bag was sealed and the panel assembly was ready for autoclave cure.

As previously discussed, the 7-foot \times 10-foot crown panel that had mechanically attached frames was cured in early April 1992. Quality of the cured panel was excellent. Cosmetic appearance of the panel was very good, and no defects were found with NDI (Figure 18).

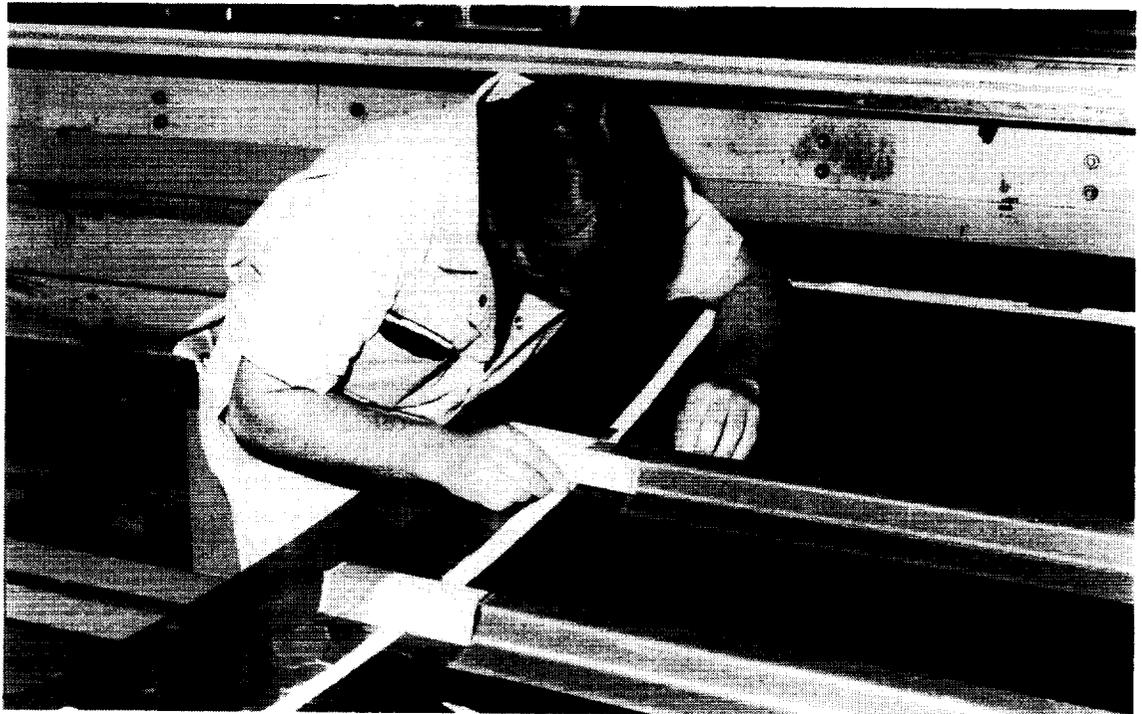


Figure 15. During assembly, stringers were located to the skin IML using a straight edge to ensure precise location.



Figure 16. The molded graphite IML flex caul was positioned on the assembled panel IML.

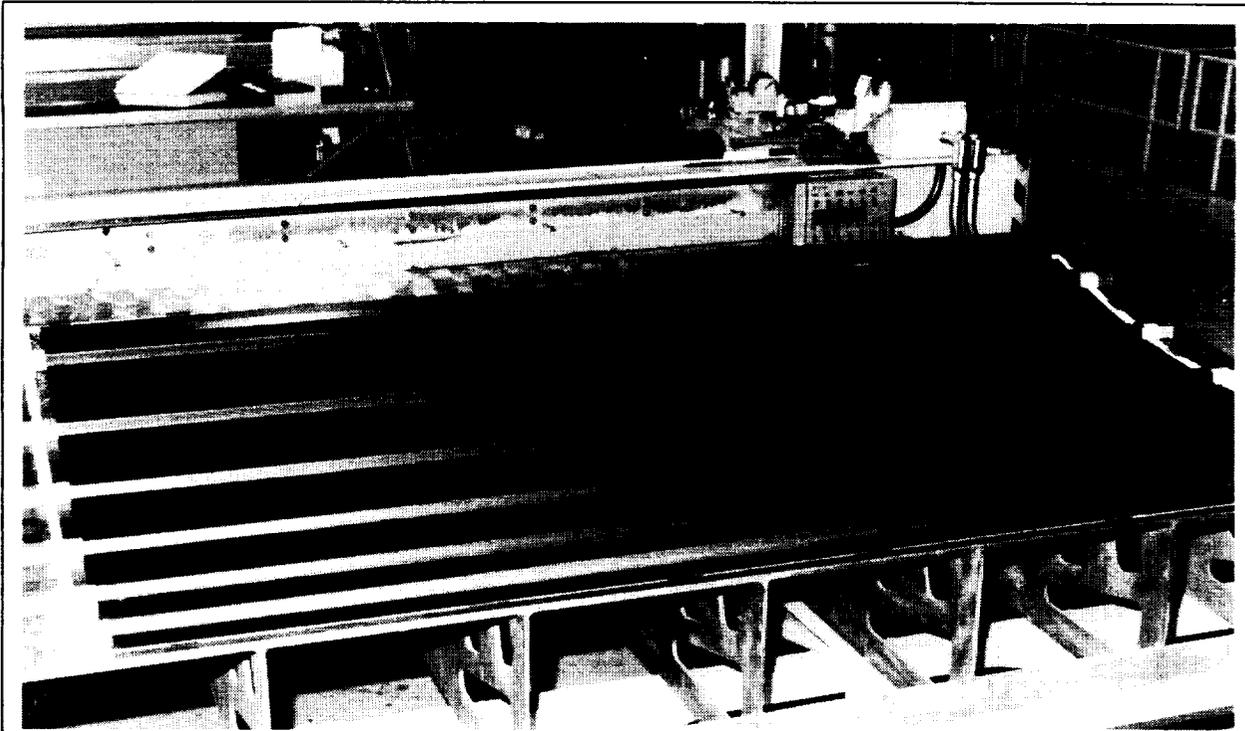


Figure 17. Boeing ATCAS crown panel was assembled and ready for cure.

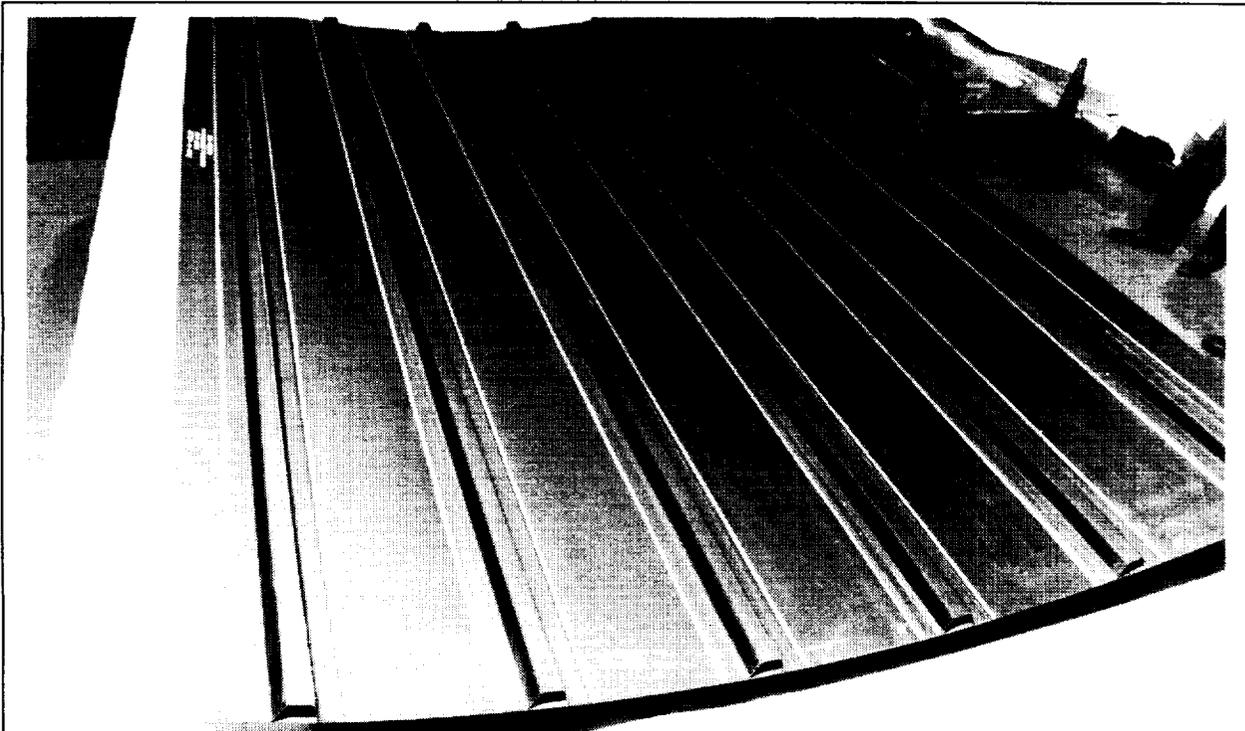


Figure 18. Boeing ATCAS crown panel had a very good cosmetic appearance; no defects were found with NDI.

Hercules manufacturing process was very successful in producing a large tow placed skin with co-cured hat stringers (Figures 19, 20, and 21).

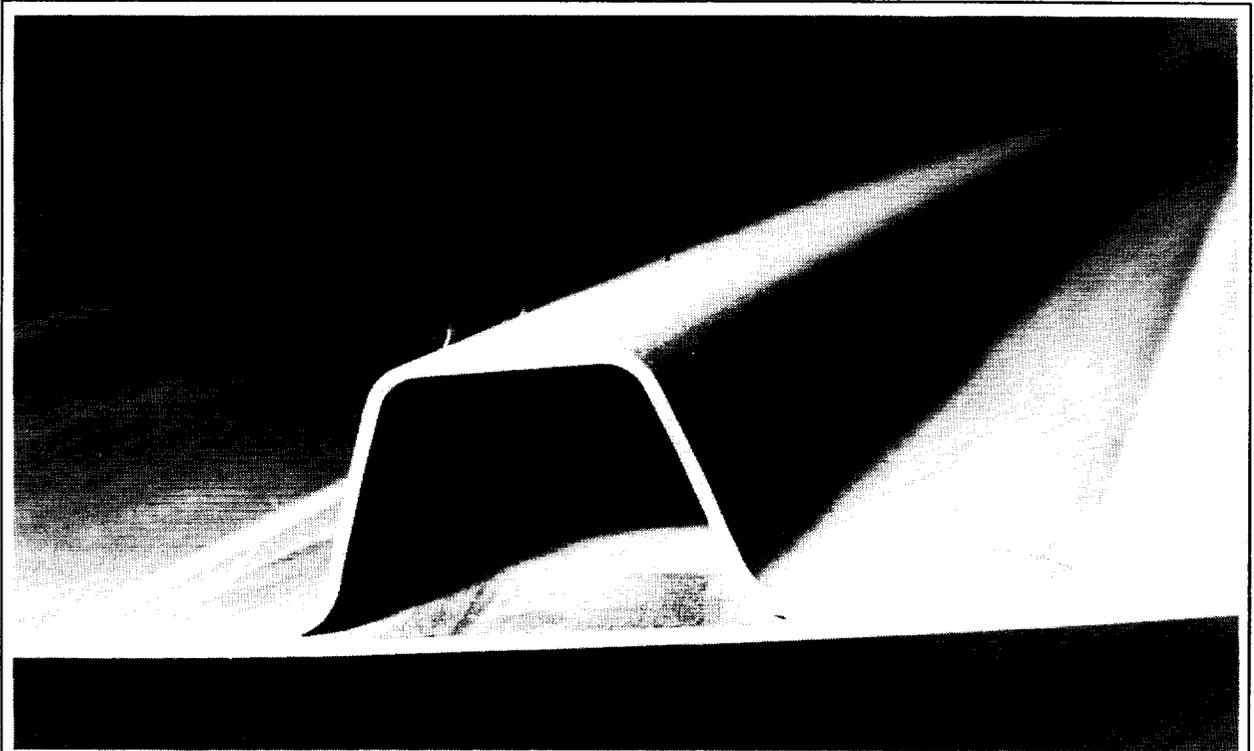


Figure 19. ATCAS crown panel hat stringer.

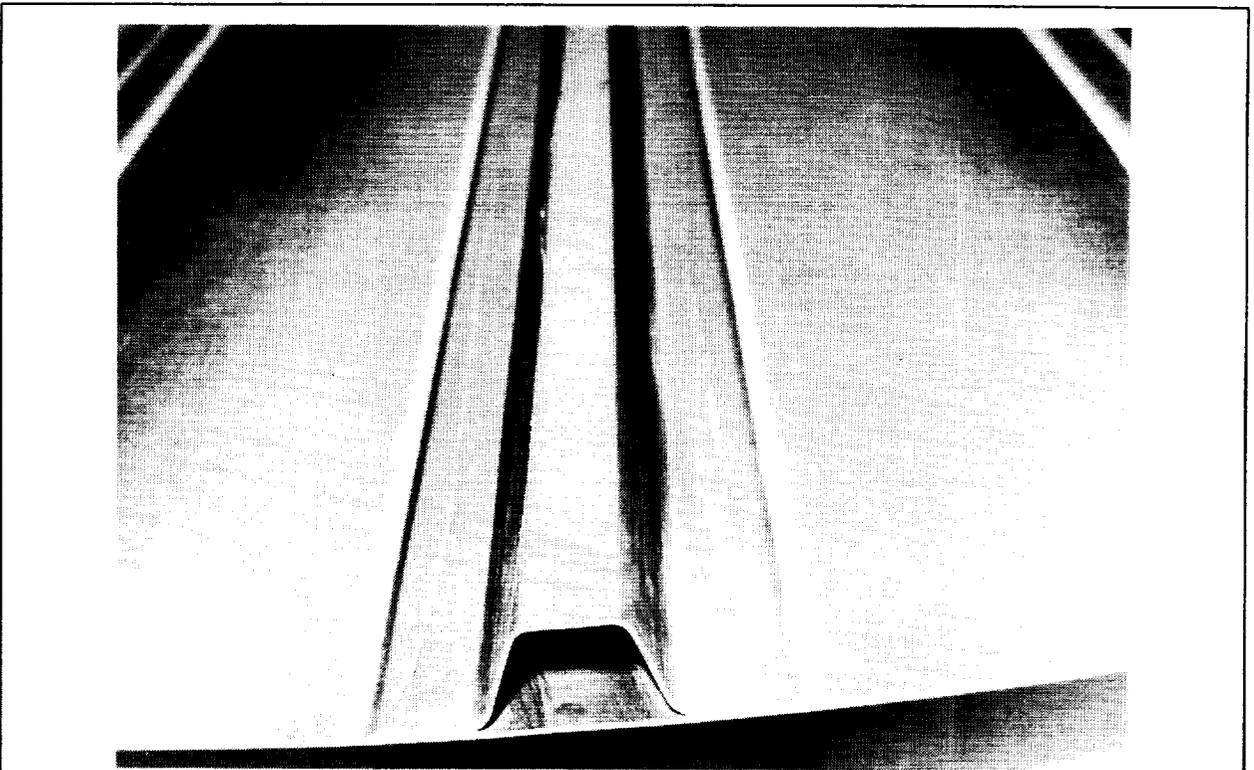


Figure 20. ATCAS crown panel hat stringer.

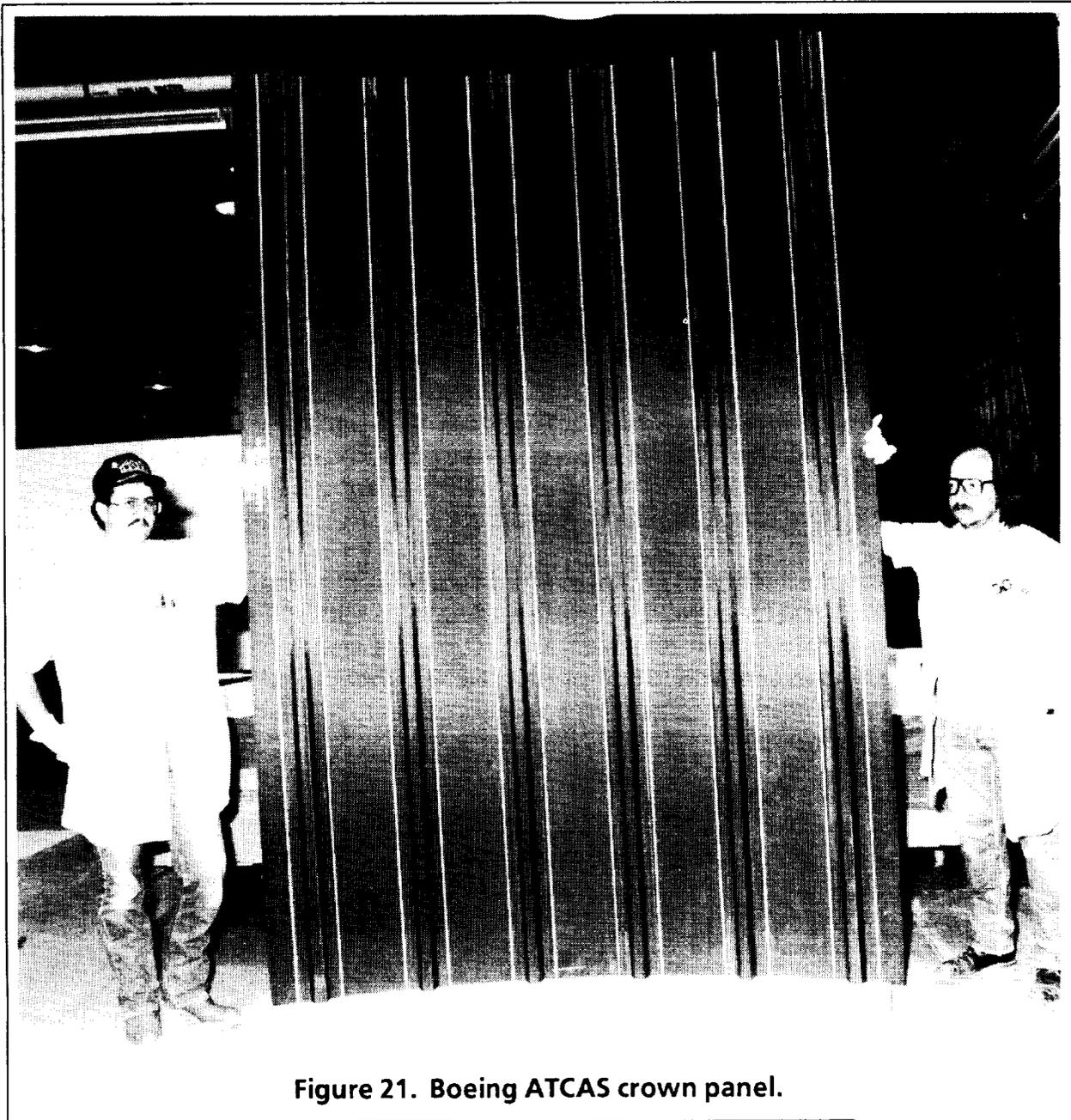


Figure 21. Boeing ATCAS crown panel.

The panel with the co-cured stringers and co-bonded frames will be cured in late May 1992. This process was successfully demonstrated on small demonstration panels. We believe it will also be successful on the 7-foot \times 10-foot crown panels.

SUMMARY

The process used to fabricate subscale crown panels with co-cured stringers and mechanically attached frame sections appears to be lower in risk than the co-bonded

frame process. The tooling concept uses fewer tooling pieces and lower cost tooling. Panels can be cured on an aluminum cure mold instead of the low CTE Invar mold. The full-length, one-piece IML flex caul has produced excellent results every time it has been used. The combination of the OML cure mold and IML molded caul produces a consistent, excellent quality panel. This process uses tried and proven composite structures manufacturing techniques (OML caul mold), and combines them with the automated tow placement process to achieve cost effectiveness. We believe this process is now production ready.

The process used to fabricate subscale crown panels with co-cured stringers and co-bonded frame sections would probably have lower recurring costs because the frame assembly effort is eliminated. At the time this paper was prepared, Hercules had not cured one of the large 7-foot \times 10-foot ATCAS panels with co-bonded frames; therefore, our data for this process were limited to small process trial panels. We believe this process will need more development, but when it is fully mature, it will be very attractive for commercial aircraft crown panel production.

Both processes are based on automated tow placement of fuselage crown panels on a cylindrical mandrel that is large enough to allow fabrication of four panels in one winding. The tow placement test panels made for the NASA ACT Program have performed well in compression-after-impact and tension fracture testing. The automated tow placement process appears to be ideally suited for production of commercial aircraft fuselage structures.